(12) UK Patent Application (19) GB (11) 2 272 294 (13) A

(43) Date of A Publication 11.05.1994

(21) Application No 9322206.5

(22) Date of Filing 28.10.1993

(30) Priority Data
(31) 07973515 (32) 09.11.1992 (33) US

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(51) INT CL^5
G01N 27/90 27/83

(52) UK CL (Edition M)
G1N NCDC N19B2C N19B4
U1S S1573 S1705 S1786 S2190

(56) Documents Cited
GB 0950696 A US 4510447 A

(58) Field of Search
UK CL (Edition M) G1N NCDC NCDG NCDN
INT CL^5 G01N 27/83 27/87 27/90
ONLINE DATABASES: WPI

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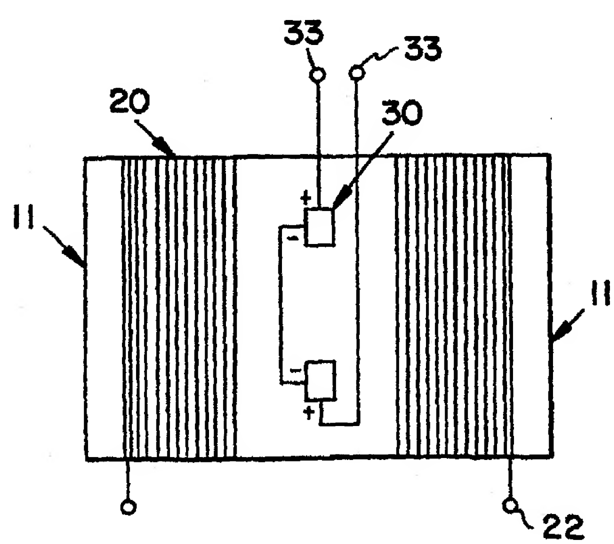
(54) **Detecting defects on covered metal components**

(57) Defects such as corrosion on the exterior of a component such as a metal pipe, tank, vessel or support structure which is insulated by a coating or cover, are detected by a low frequency eddy current system. A magnetising yoke 11 in the shape of an inverted U wound with an excitation coil 20 is placed on the cover insulating a metal component. Alternating current supplied to coil 20 produces an alternating magnetic field which induces an eddy current which runs through the metal component between the legs of the yoke. A pair of magnetic flux sensors 30 are used in differential connection to detect changes in the magnitude, phase or direction of the eddy current and the alternating magnetic field. Several excitation coils 20 which can be articulated can be used to conform to various pipe diameters. In addition, an absolute signal response can be obtained from one of the receiver coils. Defects located on the surface of pipes or tanks covered with marine growth can be detected using the probe with either a single pair of magnetic flux sensors 30 located beneath the excitation coil 20 or a plurality of magnetic flux sensor pairs differentially connected.

FIG. 7



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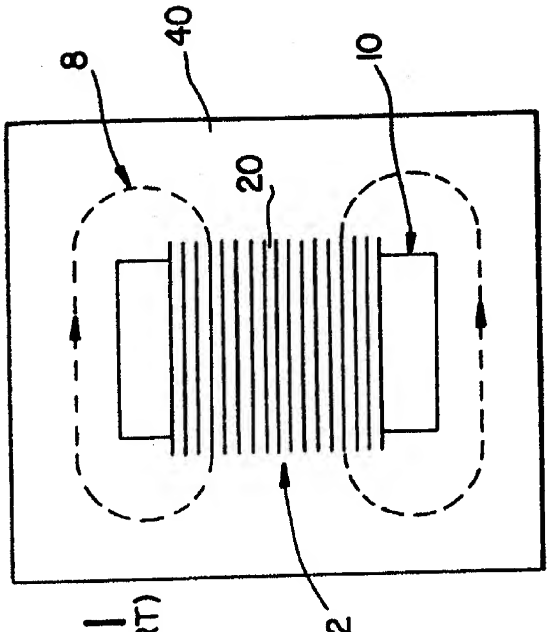


FIG. 1
(PRIOR ART)

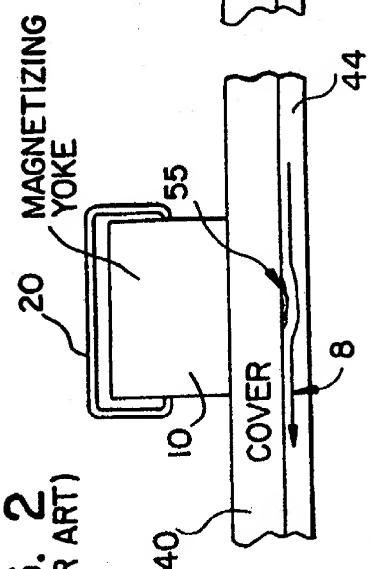


FIG. 2
(PRIOR ART)

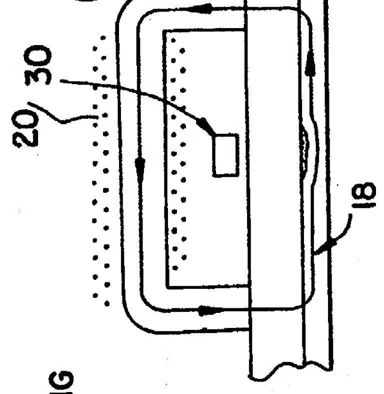


FIG. 3
(PRIOR ART)

FIG. 4
(PRIOR ART)

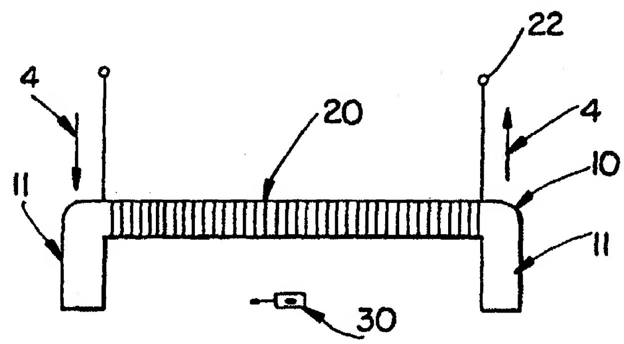


FIG. 5
(PRIOR ART)

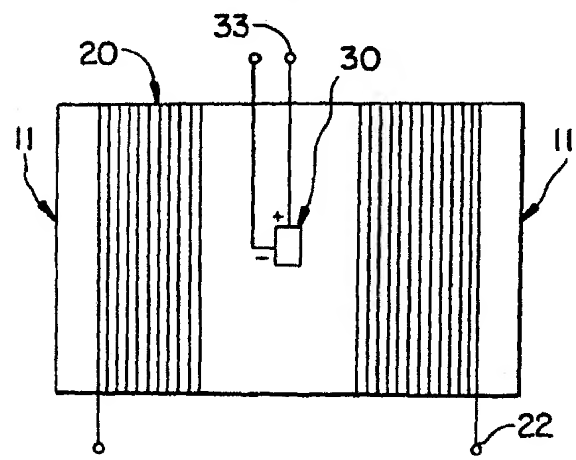


FIG. 6

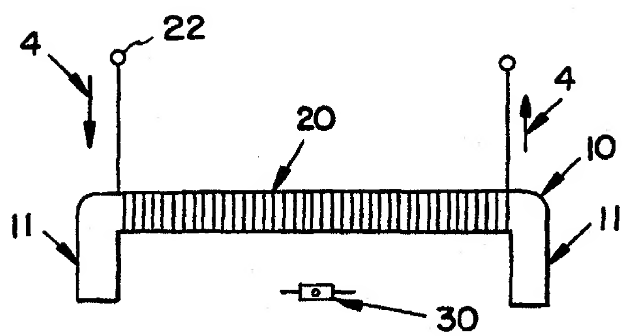


FIG. 7

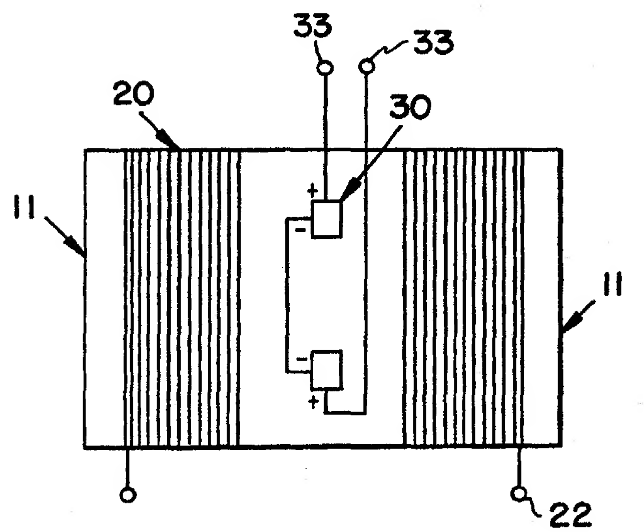


FIG. 8

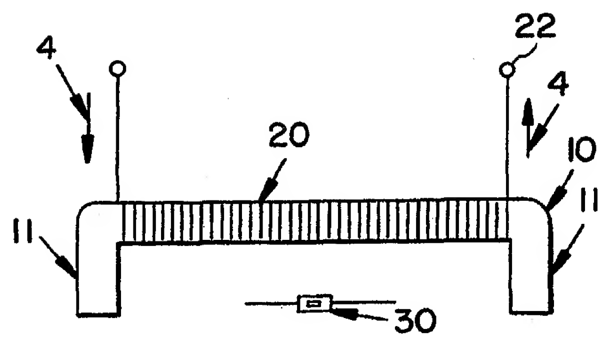


FIG. 9

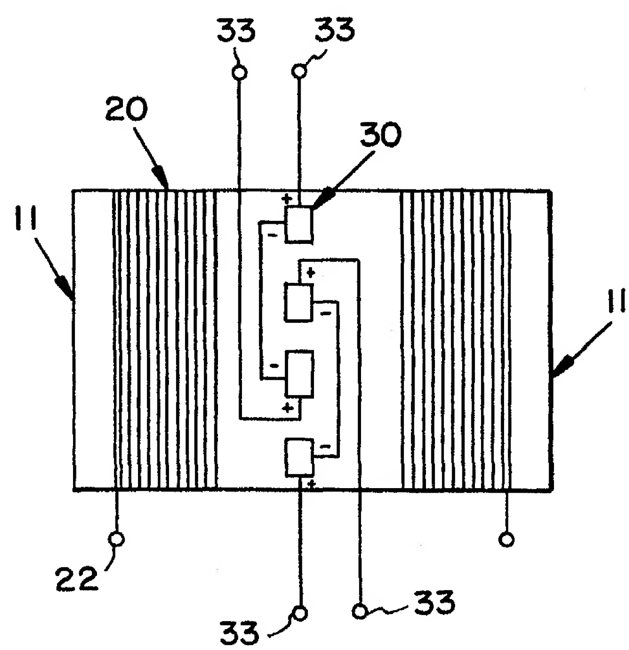


FIG. 10

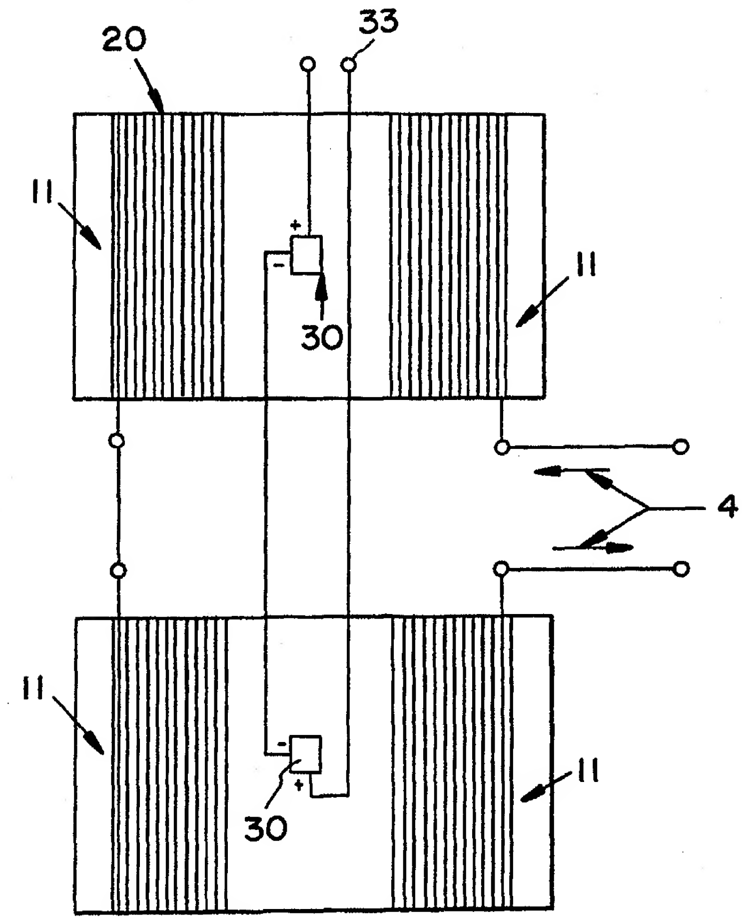


FIG. 11

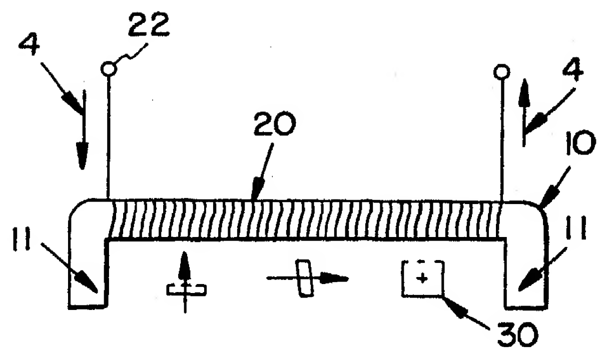


FIG. 12

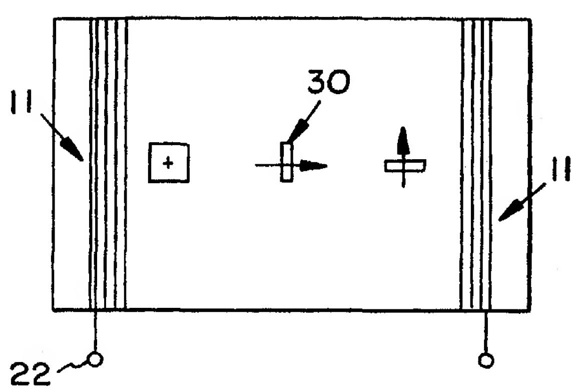


FIG. 13

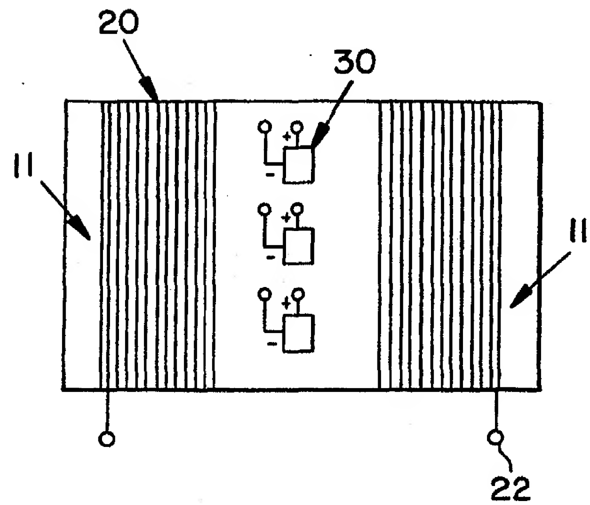


FIG. 14

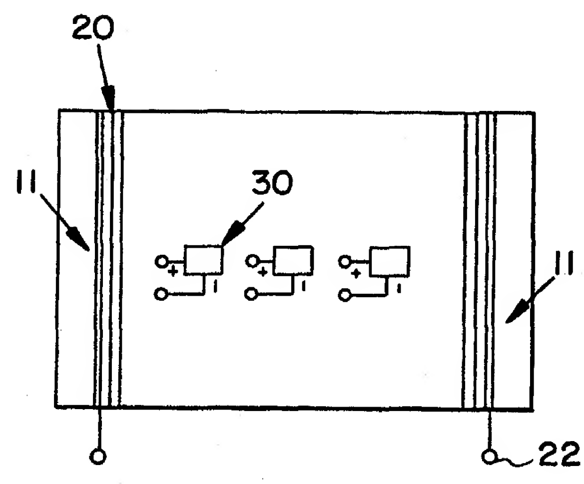
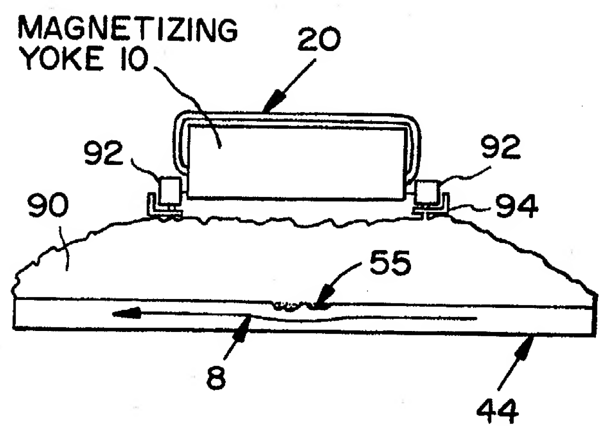


FIG. 15



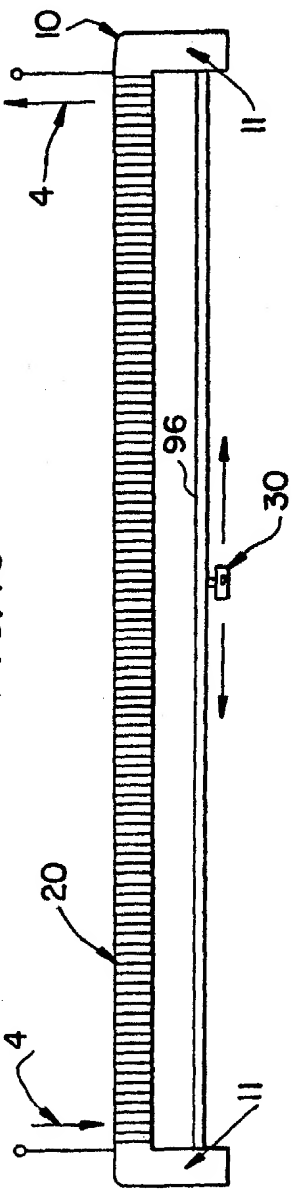


FIG. 16

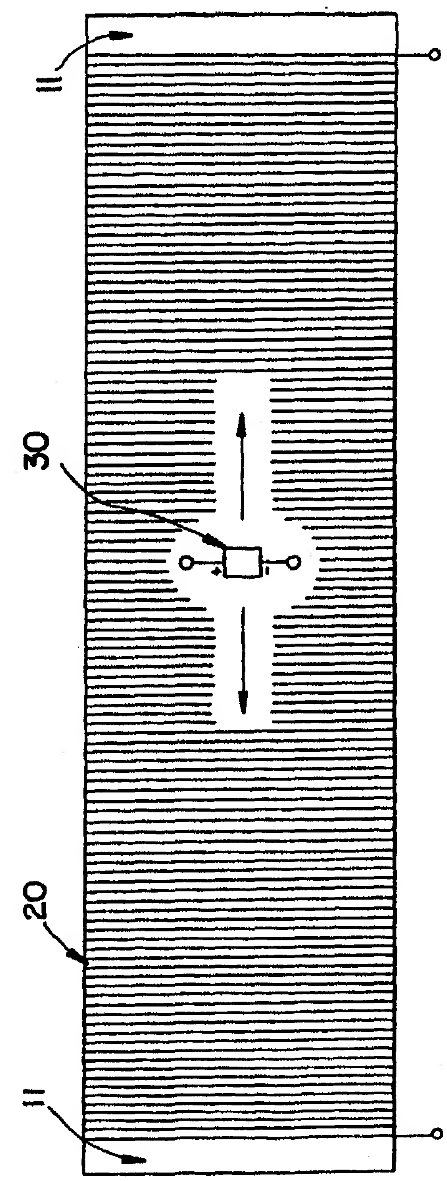


FIG. 17

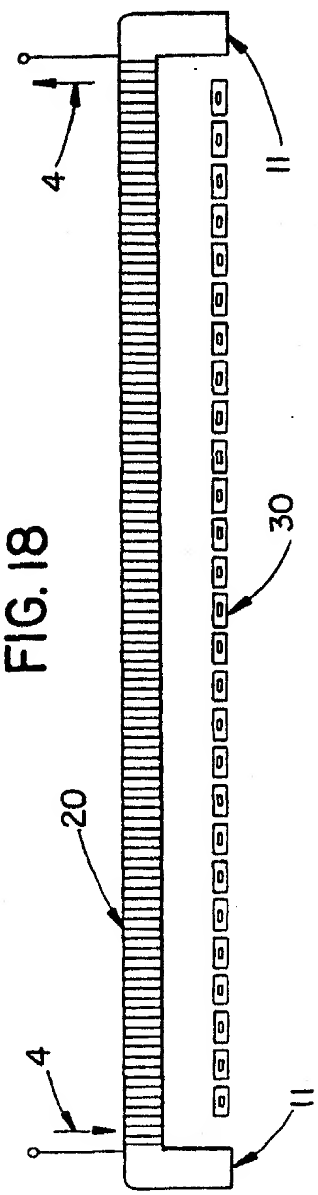


FIG. 18

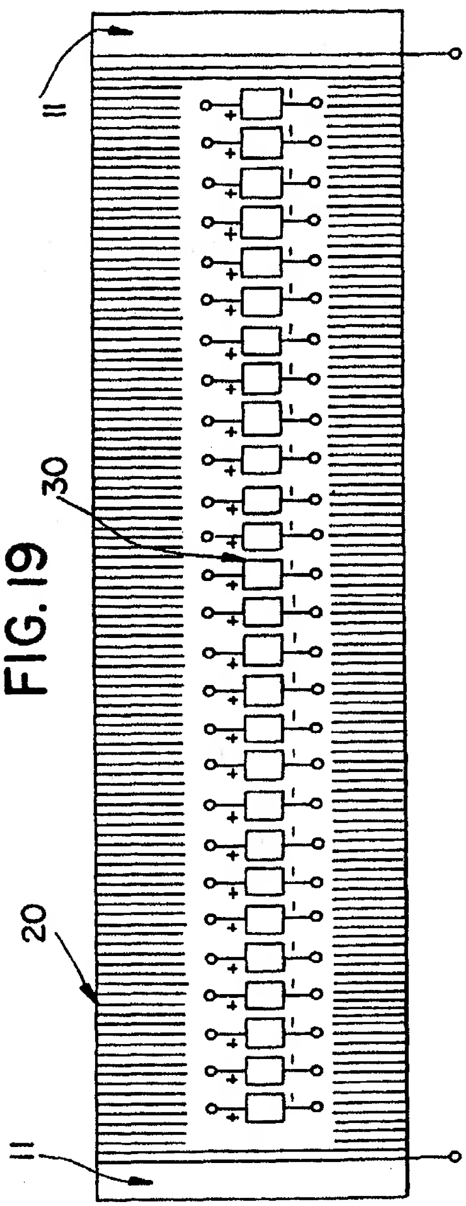


FIG. 19

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DETECTING DEFECTS ON METAL COMPONENTS

The present invention relates to the detection of defects on metal components, and in particular but not exclusively to detecting corrosion on a component that may be covered by various materials.

Corrosion on the exterior of components such as pipes, vessels and support structures is a pervasive problem throughout the petroleum and chemical process industry costing many millions of dollars annually. A majority of these components are covered with material such as insulation which promotes the corrosion by entrapment of water at the metal/cover interface. The removal of these covers and coatings for visual inspection is very costly and accounts for a substantial portion of the annual maintenance costs. Some methods have been developed in an effort to inspect covered components without removal of the insulation or covers.

One method developed for the inspection of pipes, tanks, and vessels through insulation is referred to as the Transient Electromagnetic Probe (TEMP), as disclosed in US Patent No. US-A-4 843 320 (Spies) and US Patent No. US-A-4 843 319 (Lara). This method uses the decay time of a diffusing eddy current pulse in the vessel wall to measure its thickness. The basic method is distinctly

different from the low frequency eddy current (LOFEC) method in that a transient decay time of diffusing eddy current is measured rather than flux field perturbations caused by a localized defect. Other distinguishing differences are:

1. TEMP measures the average wall thickness over a large (≥ 16 in (400 mm) diameter) - LOFEC detects the loss of surface material due to corrosion under insulation (CUI) in areas as small as 1 in (25 mm) diameter.

2. TEMP is not a scanning technique - the very large probe head must be left in place for about 3 seconds to make a single measurement. The LOFEC method can be scanned at least as fast as 4 to 6 in/sec (100 to 150 mm/sec) continuously producing output signals. Therefore, the LOFEC technique can be used as an inspection as opposed to a sampling tool.

3. There is no evidence that the TEMP method can handle the significant "artifacts" that produce signal perturbations in electromagnetic testing - these are aluminium cover overlaps, carbon steel retaining wires under the aluminium, circumferential weld beads, hidden taps or plugs, nearby support brackets, steam trace lines, etc. The LOFEC method has been designed to

eliminate or minimize the effects of all those artifacts.

A second method which has been developed for the CUI problem is the portable, real-time x-ray system (LIXI ®). Low energy x-rays are directed tangentially to the pipe so that they penetrate the insulation but not the pipe wall, thus imaging the corrosion area. This technique is much too slow to be used as an inspection tool to cover long lengths of pipe. The slow speed is due to a very limited field of view and the many tangential shots required to look at just one axial location on the pipe. It would be best suited to do spot checks for confirmation of corrosion damage after detection by a scanning method such as LOFEC. A second serious problem with the portable x-ray method is that scale in the corrosion site may tend to hide the corrosion damage.

In response to the deficiencies found in the methods listed above, a low frequency eddy current (LOFEC) method was developed for detecting corrosion and other defects on the surfaces of metal components that are covered with various materials such as paint, foam rubber, marine growth, calcium silica insulation and relatively thin metal sheets. The object of the LOFEC method is to detect surface defects such as corrosion on the component while leaving the covering material intact.

Figs. 1-5 illustrate a basic LOFEC probe generally designated 2 used for detection of surface defects such as corrosion under insulating covers. The

LOFEC probe depicted in Figs. 1-5 comprises an inverted U-shaped yoke 10 having legs 11 placed on a uniform manufactured cover 40 of a component 44 such as a steel plate. An excitation coil 20 is wound about the magnetizing yoke 10 between the legs 11. An alternating current 4 composed of one or more sinusoidal components is generated and applied to terminals 22 of the excitation coil 20. This alternating current 4 produces an alternating magnetic field 18 in the inverted U-shaped yoke 10. The yoke 10 guides the magnetic field through the cover 40 and into the component 44 beneath. If the component 44 is a ferromagnetic steel, the magnetic field 18 will be concentrated in the plate and directed from one leg of the yoke 10 toward the other. The alternating field 18 induces eddy currents 8 in the steel and other metals, (e.g., aluminum covers), located between the probe and the steel. The induced currents 8 tend to flow between and around the legs 11 of the U-shaped yoke 10 as illustrated in Fig. 1. Both the current 8 and the magnetic flux 18 are concentrated in the materials near and under the yoke 10.

Fig. 3 shows that a magnetic flux sensor 30 is located between the legs 11 of the U-shaped magnetizing yoke 10 beneath the excitation coil 20. The sensor 30 lies in a plane passing through the cross-section of the legs 11. The flux sensor 30 is an electronic device, such as a coil of conducting wire or a Hall element semiconductor that provides a signal response voltage proportional to the intensity of the magnetic flux 18 intercepted by the sensor 30 flux. Under normal

conditions, e.g., a uniform steel structure with no surface defects, the magnetic flux 18 and induced eddy currents 8 in the region directly under the excitation coil windings 20 are parallel to the plane formed by the sensor 30 that intersects the legs 11. The magnetic flux 18 flows from one leg 11 to the other and induced current 8 flows perpendicular to the flux 18. The presence of a near surface defect 55 in the steel component 44, such as corrosion, causes a change in the magnitude, phase and direction of the induced currents 8 and associated magnetic field 18 within the steel 44 and in the region between the steel 44 and the probe 2.

Surface defects 55 are identified by scanning the probe 2 over the cover 40 of the structure 44 and detecting the signal response voltage, observed at terminals 33 of the flux sensor 30.

However, presently there is no known method or device for reducing or minimizing extraneous and unwanted signal responses caused by variations in the geometry and electromagnetic properties of the component 44 when using the LOFEC technique.

Additionally, no method or device is known which can detect defects on metal components covered with marine growth while minimizing extraneous signal responses.

According to one aspect of the invention there is provided a method of detecting a defect on a metal component having a cover, the method comprising:

winding an excitation coil around a magnetic yoke;

placing a pair of magnetic flux sensors differentially connected with respect to each other in an area underneath the yoke;

placing the yoke of ferromagnetic material on the cover over the component;

applying an alternating current to the excitation coil for producing an alternating magnetic field through the yoke thereby inducing eddy currents in the component, both the alternating magnetic field and the eddy current having a magnitude, a phase and a direction;

moving the yoke along the cover of the component thereby scanning for defects; and

monitoring the alternating magnetic field and the eddy current using the sensors, for changes in at least one of the magnitude, the phase and the direction which is indicative of defects on the component.

According to further aspects of the invention there are provided methods of and devices for detecting defects on metal components, even when the components are covered with marine growth.

A preferred embodiment of the invention provides a LOFEC method and device for detecting corrosion on a covered metal component while at the same time minimizing extraneous and unwanted signal responses caused by variations in the properties of the component. The technique can also be used to detect the presence of defects such as corrosion on metal components covered with marine growth.

The invention will now be described by way of example with reference to the accompanying drawings, throughout which like parts are referred to by like references, and in which:

Fig. 1 is a top view of a known probe for a low frequency eddy current system;

Fig. 2 is a side view of the probe of Fig. 1;

Fig. 3 is a cross-sectional front view of the probe of Fig. 1;

Fig. 4 is a partial front view of the probe of Fig. 1;

Fig. 5 is a bottom view of the probe of Fig. 1;

Fig. 6 is a partial elevated front view of a probe according to an embodiment of the present invention;

Fig. 7 is a bottom view of the probe shown in Fig. 6;

Fig. 8 is a partial front view of a second embodiment of the present invention;

Fig. 9 is a bottom view of the second embodiment according to Fig. 8;

Fig. 10 is a bottom view of a third embodiment of the present invention;

Fig. 11 is a partial front view illustrating the orientation of a magnetic flux sensor embodying the present invention;

Fig. 12 is a bottom view of the orientation of the magnetic flux sensor according to Fig. 11;

Fig. 13 is a bottom view of a fourth embodiment of the present invention;

Fig. 14 is a bottom view of a fifth embodiment of the present invention;

Fig. 15 is a side view of a sixth embodiment of the present invention for detecting defects through marine growth;

Fig. 16 is a side view of a seventh embodiment of the present invention;

Fig. 17 is a bottom view of the embodiment shown in Fig. 16;

Fig. 18 is a side view of an eighth embodiment of the present invention; and

Fig. 19 is a bottom view of the embodiment shown in Fig. 18.

Referring to Figs. 6 and 7, the present invention embodied therein comprises a deep penetration eddy current (DPEC) system having a magnetizing yoke 10 of the inverted U-shaped design with legs 11 and wrapped by an excitation coil 20 for carrying a current 4 and for ultimately producing a magnetic flux while being moved along the surface of a cover of a metal component for scanning and detecting corrosion on the metal component. Throughout the drawings, the same reference numerals are used to designate the same or functionally similar parts.

As illustrated in Fig. 7, a plurality of magnetic flux sensors 30 are used beneath the excitation coil 20 in concert in order to detect perturbations in the magnetic flux caused by defects in the surface of the steel component, while at the same time providing for a reduction and minimization of unwanted and extraneous signal responses caused by variations in the structure of the components which is being inspected.

Fig. 7 shows that two magnetic flux sensors 30 are located and centred beneath the excitation coil 20. The sensors 30 are oriented such that a magnetic flux component that is upward and parallel to the centre axis of both sensors 30 produces a positive signal from one sensor and a negative signal from the other sensor.

This result can be achieved through a winding of one sensor coil in the clockwise direction and the other sensor coil in the counter-clockwise direction.

The sensors 30 are then connected in series opposing so that signal responses to a common magnetic flux will subtract. By using this arrangement, perturbations in the magnetic flux caused by overlapping ends of aluminum covers and uniform steel wire used for securing the insulation or cover to the pipes will result in a much smaller signal response.

Figs. 8 and 9 illustrate that two separate differential connections of sensors 30 are employed beneath the excitation coil 20.

Fig. 10 illustrates the present invention comprising a plurality of magnetizing yokes 10 having excitation coils 20. The magnetic flux sensor 30 is provided beneath each excitation coil 20 and is arranged in differential connection between a corresponding magnetic flux sensor 30.

The configuration illustrated in Fig. 10 is critical to the CUI application. By having two or more separate elements (each comprised of a driver coil and a receiver coil), a differential response (which is necessary to reduce the effects if artifact signals such as overlaps, wires, and circumferential weld beads) can be obtained while permitting the probe to articulate to fit the contour of pipes of varying diameters.

In addition, one of the receiver coils is used to obtain an "absolute" (as opposed to "differential") response. The direction and magnitude of the absolute

signal can be used to determine whether signal sources are due to metal loss (i.e., CUI) or added metal (wires, taps, weld beads, etc.). This determination is based on the fact that the absolute signal response will have opposite polarity.

Figs. 11 and 12 illustrate that magnetic flux sensors 30 are positioned beneath the excitation coil 20 and can be oriented with their axes in one of several directions.

Figs. 13 and 14 show that the magnetic flux sensors 30 in linear arrays are oriented in different directions, either parallel or perpendicular to the excitation coil 20.

Fig. 15 illustrates how the present invention can be used to detect defects on a component such as a metal plate 44 or metal tank encased by irregular marine growth 90 using a magnetizing yoke 10 and excitation coil 20 mounted on wheels or rollers 92 with a track 94. Track 94 includes two angle members or guide rails positioned either vertically or horizontally to allow the wheels 92 to freely roll while simultaneously scanning in a given direction. In detecting defects such as corrosion 55 engulfed by the marine growth 90, a flux sensor 30 can be used by itself or in differential connection with other flux sensors 30, as illustrated in Fig. 7.

Figs. 16 and 17 show still another embodiment of the probe in accordance with the present invention. This probe differs from the previous probe configurations in two respects. First, the magnetizing

yoke 10 is elongated or enlarged so that the distance between the legs 11 of the yoke 10 is increased to as much as about four or five feet. Second, the magnetic flux sensor(s) 30 are scanned while the magnetic flux sensor 30 in the scan direction indicated by the arrows in Fig. 17. Suitable scanning means 96 includes stepper motors capable of moving sensor 30 which may be automatic or manually controlled.

Figs. 18 and 19 show yet another embodiment similar to Figs. 16 and 17, but there is a fixed array of sensors 30 that are multiplexed to scan the component. The fixed array of sensors provides the advantages of reduced size, weight and the elimination of moving parts. Inspection of a relatively large area can be accomplished by simply holding the magnetizing yoke 10 against the component and performing the automatic multiplexing and signal response sampling of the sensor array. Advantages of the embodiments shown in Figs. 16 - 19 include the following.

The probe defects such as corrosion on the near surface of components without removing coatings and covers of various materials.

The embodiment of Figs. 18 and 19 provides a reduction in the size and weight of the scanning mechanism compared to that required to scan both the magnetizing yoke and sensor as a unit over a component.

Stationary magnetic flux sensors in arrays extending from one leg of the magnetizing yoke to the other can be sampled in sequence by using multiplexers to detect the changes in magnetic flux caused by defects

in the component, thereby eliminating the requirement for moving parts to inspect the component.

Two or more probes can be aligned side-by-side and parallel to each other to cover larger rectangular areas on the cylindrical surfaces of pipes and tanks with one simple attachment of the probe configuration to the surface of the test component, thereby reducing the time and cost for inspection.

This probe design containing a fixed array of magnetic flux sensors allows a means for sensors, associated electrical cables and on-probe electronics to be sealed for use under water.

Signal responses caused by variables other than defects in the surface of the covered component can be reduced further by multifrequency mixing. The LOFEC instrumentation is programmed to generate excitation currents composed of two or more sinusoidal components. Signal responses for each of these components are detected and applied to a formula having the general form described by the equation:

$$P = F\ [S(1),\ S(2), \ldots\ S(n)] \qquad (1)$$

where the value of P predicts the presence of a surface defect or some characteristic of the defects such as depth or length.

The terms $S(1)$, $S(2)$, ...$S(n)$ are the signal responses associated with each sinusoidal frequency component.

The function F[S(1), S(2),...S(n)] in general can take various forms using first, second, third, etc., powers of the terms S(1), S(2)... S(n).

For example, the signal responses to dents and overlaps in aluminum covers encountered while looking for corrosion on steel pipes, can be reduced by the predictive formula described in the equation below:

$$P(\text{corrosion}) = K(1) \times S(1) - K(2) \times S(2) \qquad (2)$$

where S(1) is the signal response for a low frequency component, e.g. 20HZ, and S(2) is the signal response for a significantly higher frequency component, e.g., 160 HZ. K(1) and K(2) are weighting coefficients.

Since the high frequency excitation fields and induced eddy currents are concentrated in thin aluminum covers near the probe, subtraction of the weighted signal response S(2) from the weighted signal response S(1) reduces the signal caused by overlaps and dents in the aluminum covers.

There are several advantages of the present invention as listed below.

First, the invention provides a means for generating magnetic fields that penetrate through covers and coatings, such as insulation and aluminum sheets, to detect defects on the near surface of ferromagnetic components, such as steel pipes and tanks.

Second, the size and shape of the magnetic yoke and excitation coil provide for increased penetration of the time changing magnetic fields and associated eddy

currents that are induced in the ferromagnetic components under interrogation.

Third, location of the magnetic flux sensing coil in the space under the excitation coil and between the legs of the magnetizing yoke provides a means for detecting changes in the direction, amplitude and phase of the induced eddy current and associated magnetic fields in the vicinity of a defect.

Fourth, the use of pairs of sensors electronically connected in differential pairs provides a means of reducing unwanted signal response caused by variations in the geometry and electromagnetic properties of the component.

While the specific embodiments of the invention have been shown and described in detail to illustrate the application of the principles of the invention, it will be understood that the invention may be embodied otherwise without departing from such principles.

CLAIMS

1. A method of detecting a defect on a metal component having a cover, the method comprising:

winding an excitation coil around a magnetic yoke;

placing a pair of magnetic flux sensors differentially connected with respect to each other in an area underneath the yoke;

placing the yoke of ferromagnetic material on the cover over the component;

applying an alternating current to the excitation coil for producing an alternating magnetic field through the yoke thereby inducing eddy currents in the component, both the alternating magnetic field and the eddy current having a magnitude, a phase and a direction;

moving the yoke along the cover of the component thereby scanning for defects; and

monitoring the alternating magnetic field and the eddy current using the sensors, for changes in at least one of the magnitude, the phase and the direction which is indicative of defects on the component.

2. A method according to claim 1, wherein a plurality of pairs of magnetic flux sensors differentially connected with respect to each other are placed in the area between the excitation coil and the cover of the component.

3. A method according to claim 1 or claim 2, wherein the

pair of magnetic flux sensors differentially connected with respect to each other are oriented in a plurality of directions.

4. A method according to claim 1, claim 2 or claim 3, wherein a plurality of magnetic flux sensors are placed in the area between the excitation coil and the cover of the component.

5. A method according to claim 4, wherein each magnetic flux sensor is oriented in the same direction.

6. A method according to claim 1, wherein a plurality of yokes are placed on the cover of the component and a magnetic flux sensor of one yoke is differentially connected with a magnetic flux sensor of another yoke.

7. A method according to claim 6, wherein the plurality of yokes are constructed to articulate so as to accommodate varying pipe diameters while still obtaining both a differential and an absolute response.

8. A method of detecting a defect on a metal component coated with irregular marine growth, the method comprising:

winding an excitation coil around a magnetic yoke;

placing a magnetic flux sensor underneath the yoke;

placing the magnetizing yoke on the marine growth over the component;

applying an alternating current to the excitation coil for producing an altering magnetic field through the yoke thereby inducing an eddy current in the component, both the alternating magnetic field and the eddy current having a magnitude, a phase and a direction;

moving the yoke along the cover of the component for scanning for defects; and

monitoring the alternating magnetic field and the eddy current by the sensor for changes in at least one of the magnitude, the phase and the direction.

9. A method according to claim 8, wherein a pair of magnetic flux sensors differentially connected with respect to each other are placed in an area between the excitation coil and the marine growth.

10. A method according to claim 8 or claim 9, wherein a plurality of pairs of magnetic flux sensors differentially connected with respect to each other are placed in the area between the excitation coil and the marine growth of the component.

11. A method according to claim 8, claim 9 or claim 10, wherein the pair of magnetic flux sensors differentially connected with respect to each other are oriented in a plurality of directions.

12. A method according to any one of claims 8 to 11,

wherein a plurality of magnetic flux sensors are placed in the area between the excitation coil and the marine growth of the component.

13. A method according to any one of claims 8 to 12, wherein each magnetic flux sensor is oriented in the same direction.

14. A method according to claim 8, wherein a plurality of yokes are placed on the marine growth of the component and a magnetic flux sensor of one yoke is differentially connected with a magnetic flux sensor of another yoke.

15. A method according to claim 14, wherein the plurality of yokes are constructed to articulate so as to accommodate varying pipe diameters while still obtaining both a differential and an absolute response.

16. A device for detecting a defect on a metal component having a cover, the device comprising:

a magnetizing yoke having a body supported by a plurality of legs, the legs being capable of contacting the cover and supporting the body over the cover such that when the yoke is placed on the cover of the component, a space is formed between the body, the legs and the cover, the yoke being moveable about the cover;

an excitation coil wound around the body of the yoke between the legs for receiving an alternating current and

producing an alternating magnetic field through the yoke thereby inducing an eddy current through the component, the alternating magnetic field and the eddy current having a magnitude, a phase and a direction; and

a pair of magnetic flux sensors differentially connected with respect to each other located within the space for detecting changes in the magnitude, the phase and the direction of the alternating magnetic field and the eddy current.

17. A device according to claim 16, wherein a plurality of pairs of magnetic flux sensors differentially connected with respect to each other are located within the space.

18. A device according to claim 16 or claim 17, wherein the pair of magnetic flux sensors differentially connected with respect to each other are oriented in a plurality of directions.

19. A device according to claim 16, claim 17 or claim 18, wherein a plurality of magnetic flux sensors are located within the space.

20. A device according to claim 16, wherein each magnetic flux sensor is oriented in the same direction.

21. A device according to claim 16, wherein a plurality of magnetizing yokes are used on the cover of the component

such that a magnetic flux sensor of one yoke is differentially connected with a magnetic flux sensor of another yoke.

22. A device according to claim 21, wherein the plurality of yokes are constructed to articulate so as to accommodate varying pipe diameters while still obtaining both a differential and an absolute response.

23. A method of detecting a defect on a metal component, the method being substantially as hereinbefore described with reference to Figs. 6 to 19 of the accompanying drawings.

24. A device for detecting a defect on a metal component, the device being substantially as hereinbefore described with reference to Figs. 6 to 19 of the accompanying drawings.